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Implications of Non-Standard CP Violation in Hadronic B -Decays

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Abstract

We investigate a class of models for new physics which could produce a large difference in $\sin 2\beta$ between $B^0 \rightarrow J/\psi K_S$ and the “pure penguin” mode $B^0 \rightarrow \phi K_S$. In such models, the dominant effect is through a Z-penguin and therefore a pattern of deviation in $\sin 2\beta$ as measured in $B^0 \rightarrow \chi_1 K_S; \eta_c K_S; J/\psi K_S$ and $\psi' K_S$ is predicted. If the preliminary data concerning the discrepancy between $J/\psi K_S$ and ϕK_S proves correct in magnitude, discrepancies in these other modes would likely be observable. We also consider the effects such new physics could have on the B_s system and the isospin analysis of $B \rightarrow K\pi$. We compare this scenario with a scenario where contributions to $\sin 2\beta$ in various modes is produced by gluino loops and down squark mixing.

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1 Introduction

The Standard Model (SM) provides a consistent explanation of CP violation which has been observed in the Kaon system and, more recently at the BaBar and BELLE B-factories. Indeed, the B-factories provide a number of decays where CP violation should be evident and therefore will allow stringent testing of the SM mechanism of CP violation.

The most well established B-factory result is the determination of $\sin 2\beta$ from the decay $B \rightarrow \psi K_S$ and related processes [1]-[3]:

$$\sin 2\beta_{\psi K} = +0.734 \pm 0.054 \quad (1)$$

The SM expectation derived from the Kaon sector, the rate of $b \rightarrow u$ transitions and the rate of $B\bar{B}$ oscillation is that [4]:

$$0.64 \leq \sin 2\beta_{fit} \leq 0.84 \quad (95\% \text{ C.L.}) \quad (2)$$

and so there is excellent agreement with the above result.

A firm prediction of the SM is that the $b \rightarrow s$ penguin would have the same weak phase to order λ^2 as the $b \rightarrow c\bar{c}s$ transition driving $B \rightarrow \psi K_S$, see [5] for experimental tests of the SM back ground. It therefore follows that in the “pure penguin” decay $B \rightarrow \phi K_S$ the time dependent CP violation would be the same as in $B \rightarrow \psi K_S$. Early results from the B-factories, however, seem to contradict this. If we interpret the time dependence of $B \rightarrow \phi K_S$ as a measure of $\beta, \beta_{\phi K_S}$, the experimental results are:

$$\begin{aligned} \sin 2\beta_{\phi K_S} &= -0.18 \pm 0.51 \pm 0.07 \quad (\text{BaBar[6]}) \\ \sin 2\beta_{\phi K_S} &= -0.73 \pm 0.64 \pm 0.22 \quad (\text{BELLE[7]}) \\ \sin 2\beta_{\phi K_S} &= -0.38 \pm 0.41 \quad (\text{Average}) \end{aligned} \quad (3)$$

The result Eq. (3) provide a suggestive contrast to $\beta_{\phi K_S}$ in Eq. (1). If this 2.7-sigma discrepancy proves, with more data, to be a real difference between $\sin 2\beta_{\psi K_S}$ and $\sin 2\beta_{\phi K_S}$ then it would provide definitive evidence for new physics (NP).

This discrepancy is only possible if the NP contribution to $B \rightarrow \phi K_S$ is comparable to the SM. This places considerable constraints on the nature of the NP. In [8] it was argued that a promising class of models that can explain the effect involve flavor changing couplings of the Z-boson to $\bar{b}s$. Such couplings may arise either from the d -quark mass matrix if these quarks are mixed with extra vector-like down quark or through flavor changing penguin graphs containing new particles, such as the minimal supersymmetric Standard Model (MSSM) with large mixing in the up squark sector. Regardless of how the sZb coupling arise, this mechanism leads to a number of definite predictions. In this paper, we will discuss some of the implications of non-standard sZb couplings. In particular the same amplitude which gives rise to the ϕK_S anomaly should also contribute to related hadronic decays $B \rightarrow K\pi$; and indeed to the golden modes such as ψK_S and $\chi_c K_S$. The pattern of contributions to these case may provide additional evidence for this mechanism, and in general for any kind of physics beyond the SM.

While NP effects in various $b \rightarrow q_1 \bar{q}_2 q_3$ decays have been estimated e.g. [9] we investigate here differences in the CP asymmetry induced by interference between mixing and decay among different final states with the *same* flavor content. If NP breaks parity and CP, we obtain in general different answers from mesons with different J^{CP} quantum numbers.

In the case of $B \rightarrow (c\bar{c})K_S$ where $(c\bar{c}) = J/\psi, \psi', \eta_c, \chi_1$ early experimental analysis have already been performed as part of the effort to determine $\sin 2\beta$ in the context of the SM. Their weighted average, in fact, enters the number given in Eq. (1) as ¹

$$\begin{aligned} \sin 2\beta_{J\Psi K_S(K_S \rightarrow \pi^+ \pi^-)} &= 0.82 \pm 0.08 \\ \sin 2\beta_{\Psi' K_S(K_S \rightarrow \pi^+ \pi^-)} &= 0.69 \pm 0.24 \\ \sin 2\beta_{\chi_1 K_S} &= 1.01 \pm 0.40 \quad (BaBar[1]) \\ \sin 2\beta_{\eta_c K_S} &= 0.59 \pm 0.32 \end{aligned} \quad (4)$$

Clearly at the present time $\sin 2\beta$ is consistent between these modes but it will be important to pursue further experimental study sensitive to the level at which NP enters the $b \rightarrow c\bar{c}s$ decay amplitude as well as in the corresponding B_s -decays. Such studies can be done at the B-factories and/or at future hadron colliders. It is important to keep in mind that these searches for NP are based on the prediction of the SM that $\sin 2\beta$ is consistent for all such modes and is independent of fits to the unitarity triangle of $\sin 2\beta$ which are currently dominated by a theory error of 14% that exceeds the experimental error in $\sin 2\beta$ by a factor of two, see Eqs. (1) and (2).

The outline of the paper is as follows. In Section 2 we work out constraints on NP from $B \rightarrow \phi K_S$ data. In Section 3 the effect of non-standard Z -couplings in hadronic 2-body decays are calculated and constraints are discussed. In Section 4 we compare the predictions of the scenario with non-SM Z-penguins with other models of NP and in Section 5 we conclude. In Appendix A we give the matrix elements of $\bar{B} \rightarrow \phi K$ and $\bar{B} \rightarrow (c\bar{c})K$ decays in terms of the effective low energy Hamiltonian. In Appendix B the initial conditions and the leading log running of the ElectroWeak penguins are specified.

2 The $B \rightarrow \phi K_S$ decay amplitude with NP

Let us now assume that $B \rightarrow \phi K_S$ receives a NP amplitude which accounts for the discrepancy in $\sin 2\beta_{\phi K_S}$. Thus, if a is the magnitude of the SM contribution and b is the magnitude of the NP contribution, then if we use a phase convention where the SM contribution is real the amplitude may be written as:

$$\begin{aligned} \mathcal{A}(\phi K_S) &= a + b e^{i(\rho+\lambda)} \\ \overline{\mathcal{A}}(\phi K_S) &= \eta(X) [a + b e^{i(\rho-\lambda)}] \end{aligned} \quad (5)$$

¹Also Belle [2] uses $J/\Psi, \Psi', \eta_c, \chi_1$ in their analysis, however, do not give the individual contributions.

where $\rho(\lambda)$ is the strong (weak) phase difference between the two contributions and $\mathcal{A}(X)$ is the amplitude for $B^0 \rightarrow X$ while $\overline{\mathcal{A}}(X)$ denotes the amplitude for $\bar{B}^0 \rightarrow X$. The factor $\eta(X)$ denotes the CP eigenvalue of the final state X , e.g. $\eta(\phi K_S) = -1$.

It follows then that the time dependent CP asymmetry may be written as:

$$a_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \rightarrow X) - \Gamma(B^0(t) \rightarrow X)}{\Gamma(\bar{B}^0(t) \rightarrow X) + \Gamma(B^0(t) \rightarrow X)} = -C_X \cos(\Delta m_B t) + S_X \sin(\Delta m_B t) \quad (6)$$

where the sine and cosine coefficients are given by:

$$\begin{aligned} C_X &= \frac{|\mathcal{A}(X)|^2 - |\overline{\mathcal{A}}(X)|^2}{|\mathcal{A}(X)|^2 + |\overline{\mathcal{A}}(X)|^2} \\ S_X &= \frac{2i\text{Im}(\mathcal{A}^*(X)\overline{\mathcal{A}}(X)e^{-2i\beta})}{|\mathcal{A}(X)|^2 + |\overline{\mathcal{A}}(X)|^2} \equiv -\eta(X) \sin 2\beta_X \end{aligned} \quad (7)$$

Here, 2β is the phase from the $B\bar{B}$ mixing defined in the phase convention of Eq.(5)².

From the observed time dependent CP violation of $B \rightarrow \phi K_S$ we may obtain some information about these amplitudes on a model independent basis. In the following we will discuss the analysis of the data in the scenarios that the strong phase difference $\rho = 0$.

In the case where there is no strong phase, then $\mathcal{A}^*\eta(X) = \overline{\mathcal{A}}$ and therefore $C_X = 0$. We can therefore extract the amplitude from the CP averaged branching ratio $\Gamma_0 = \frac{1}{2}(|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2)$ and S_X using:

$$\mathcal{A}(X) = \sigma_1 \left[\sqrt{\Gamma_0(X)} \sqrt{-i\eta(X)S_X + \sigma_2 \sqrt{1 - S_X^2}} \right] e^{-i\beta} \quad (8)$$

where $\sigma_{1,2} = \pm 1$ giving a 4-fold ambiguity. Then, given β we can determine from Eq. (5) for each value of a a value of b/a and λ by $b/a e^{i\lambda} = \mathcal{A}/a - 1$.

Data are consistent with no direct CP violation in $B \rightarrow \phi K_S$ decay:

$$\begin{aligned} C_{\phi K_S} &= -0.80 \pm 0.38 \pm 0.12 \quad (\textit{BaBar}[6]) \\ C_{\phi K_S} &= +0.56 \pm 0.41 \pm 0.16 \quad (\textit{BELLE}[7]) \\ C_{\phi K_S} &= -0.19 \pm 0.30 \quad (\textit{Average}) \end{aligned} \quad (9)$$

In Fig. 1 we show the weak phase λ as a function of the NP to SM ratio b/a for the case without a strong phase. The curves are the solutions to Eq. (8) for the central value and the ± 1 sigma range of $S_{\phi K_S} (= \sin 2\beta_{\phi K_S})$ from the data average in Eq. (3) and $\beta = 23.9^\circ$, the central value of the fit Eq. (2). The measured branching ratio $\mathcal{B}(B^0 \rightarrow \phi K^0) = 8.4 \pm 1.6 \cdot 10^{-6}$ [14] agrees within errors with the SM value, e.g. [10]. To avoid a “fine tuning” configuration i.e. a near cancellation between NP and SM we take $\sqrt{\Gamma_0(\phi K_S)}/4 \leq a \leq 2\sqrt{\Gamma_0(\phi K_S)}$. We recall that for fixed input S, Γ_0 each value of b/a gives a 4-fold solution for λ within 0 and π . Some solutions in Fig. 1 end for larger values of b/a because of the lower bound on a . The cut-out regions around $b/a \sim 1$ increase in

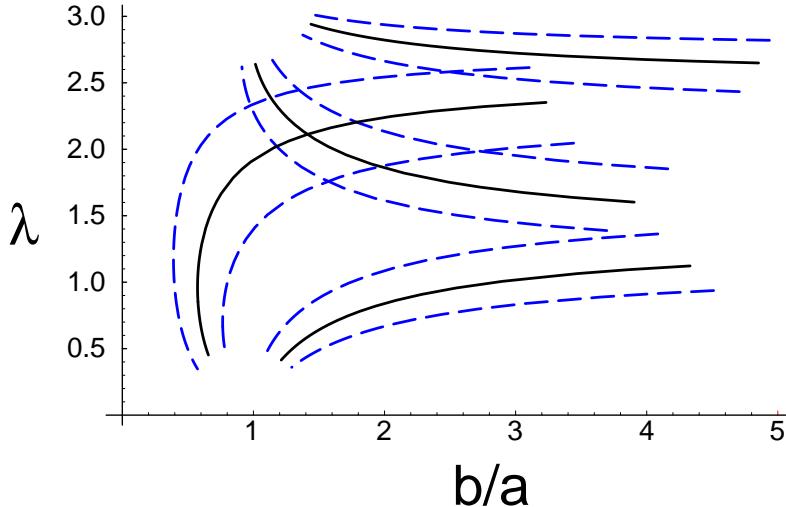


Figure 1: 4-fold solutions following from Eq. (8) in the b/a - λ plane for $S_{\phi K_S} = -0.79, -0.38, +0.03$, i.e. the central experimental value and the 1σ range for vanishing strong phase. The curves corresponding to the central value (-0.38) are solid while the curves corresponding to the 1-sigma range (-0.79, +0.03) are dashed. For details see text.

size if the upper bound on a would decrease and vice versa. We see that ratios b/a are typically order one with order one weak phase λ , similar to the findings of Ref. [10].

3 Z -penguin effects in 2-body b -decays

The Lagrangian of the effective FCNC sZb couplings maybe written as

$$\mathcal{L}_Z = \frac{g^2}{4\pi^2} \frac{g}{2 \cos \theta_W} \left(\bar{b}_L \gamma_\mu s_L Z_{sb} + \bar{b}_R \gamma_\mu s_R Z'_{sb} \right) Z^\mu + h.c. \quad (10)$$

where Z_{sb} (Z'_{sb}) denote the left (right) handed coupling strength. The sZb -couplings are experimentally constrained as

$$\sqrt{|Z_{sb} + Z_{sb\,SM}|^2 + |Z'_{sb}|^2} \leq 0.08 \quad (11)$$

which updates [11, 12], where details can be found. The bound in Eq. (11) is based on inclusive $B \rightarrow X_s e^+ e^-$ decays at NNLO [13] and corresponds to an enhancement of 2–3 over the SM value³

$$Z_{sb\,SM} = -V_{tb}^* V_{ts} \sin^2 \theta_W C_{10}^* \simeq -0.04, \quad Z'_{sb\,SM} \simeq 0 \quad (12)$$

²We comment on NP in $B\bar{B}$ mixing in Section 5.

³The experimental bounds on the branching ratios of $B \rightarrow (X_s, K, K^*) \ell^+ \ell^-$ decays have gone down, but the theoretical value has decreased from NLO to NNLO, too.

The inclusion of right handed couplings into the distributions of semileptonic $b \rightarrow s\ell^+\ell^-$ decay is straightforward since different helicities do not interfere in the limit of a vanishing strange quark mass.

Tree level Z -boson exchange and subsequent $q\bar{q}$ pair production induces NP contributions to hadronic B -decays via $b \rightarrow s\bar{q}q$. These are proportional to the $q\bar{q}Z$ coupling, which we assume to be SM like, i.e., the coupling Z_V to vector and axial vector Z_A currents are given, respectively, as $Z_V = I_{3q} - 2Q_q \sin^2 \theta_W$ and $Z_A = -I_{3q}$. Note that we use $Z_V \bar{q}\gamma_\mu q + Z_A \bar{q}\gamma_\mu \gamma_5 q$ such that the sign of Z_A is opposite to the PDG definition [14]. The values and ratio of different $q\bar{q}Z$ coupling are compiled in Table 1 for $\sin^2 \theta_W = 0.23$.

	$c\bar{c}$	$s\bar{s}$	$u\bar{u} - d\bar{d}$
Z_V	+0.19	-0.35	+0.54
Z_A	-0.5	+0.5	-1
Z_A/Z_V	-2.6	-1.4	-1.9

Table 1: Values of vector, axial vector Z -couplings and their ratio for different $q\bar{q}$ pairs.

As can be seen from the ratio Z_A/Z_V in Table 1 the $c\bar{c}$ system has the biggest spread among final states with different quantum numbers (vector versus axial vector coupling) induced by the Z -exchange. In the next Sections 3.1 and 3.2 we estimate the implications of large, in general CP violating sZb -couplings for $B \rightarrow (c\bar{c})K$ and $B_s \rightarrow (c\bar{c})\phi$ decays. Further, the couplings of Z -penguins to $I = 1$ mesons such as π^0 are very large. In Section 3.3 we investigate whether current data on $B \rightarrow K\pi^0$ decays yield additional constraints on the sZb -couplings. Note that in order to explain a deviation in CP asymmetry from the SM as large as hinted by current data the couplings $Z_{sb}^{(\prime)}$ need to be near their upper bound and with a large phase.

3.1 B -decays into charmonium

We discuss the implications of non-standard Z -penguins in the decays $B \rightarrow MK$ into charmonium $M = \eta_c, \Psi, \Psi'^\prime, \chi_0, \chi_1, \chi_2$. The NP effect in the decays is split according to the CP properties of the final $(c\bar{c})$ states. Whereas the vector mesons couple to a vector current $\sim Z_V$, the pseudoscalar and axial vector mesons couple to axial vector current $\sim Z_A$. Hence, the Z -penguin effect in η_c and χ_1 is bigger than in the vector mesons Ψ, Ψ'^\prime by a factor of 2.6, as can be read off Table 1. In the presence of a CP violating phase in the Z -contribution, this leads to a difference in $\sin 2\beta$ measured among the *golden* modes. The generic size of this effect is $\arg(P/T)P/T$ where P denotes the penguin contribution including the NP, and T is the SM tree contribution in the $b \rightarrow c\bar{c}s$ amplitude. In the SM, $\arg(P/T) \sim \lambda^2$, whereas it can be order one in the presence of NP. Since $\mathcal{B}(B \rightarrow \phi K)/\mathcal{B}(B \rightarrow (c\bar{c})K) \simeq 10^{-2}$ an order one NP effect in $b \rightarrow s\bar{s}s$ gives

up to ten percent contribution to the $b \rightarrow c\bar{c}s$ amplitude. Therefore, we expect here differences in $\sin 2\beta$ of this order.

To quantify this general prediction, we neglect for simplicity direct CP violation and obtain for the size of the NP effect

$$\sin 2\beta_{MK_S} - \sin 2\beta = \sin(2\beta - \arg(MK_S)) - \sin 2\beta \approx -\arg(MK_S) \cos 2\beta \quad (13)$$

where we expanded in small phases in $\bar{\mathcal{A}}/\mathcal{A}$ and abbreviated $\arg(\bar{\mathcal{A}}(MK_S)/\mathcal{A}(MK_S) \equiv \arg(MK_S)$. Note that $\eta(\chi_{0,2}K_S) = +1$ and -1 for $J/\Psi, \Psi', \eta_c, \chi_1$. Numerically, we obtain in the non-standard Z -scenario

$$|\arg(MK_S)| \leq \begin{cases} 0.11 & \text{for } M = \Psi, \Psi' \\ 0.25 & \text{for } M = \eta_c, \chi_1 \end{cases} \quad (14)$$

Here we varied the magnitudes and phases of Z_{sb} and Z'_{sb} independently while respecting the constraint given in Eq. (11). These numbers as well as numerical estimates of other quantities to be discussed later in the text (also for the case with $Z'_{sb} = 0$) are summarized in Table 2. Explicit formulae of the matrix elements and details can be seen in Appendix A and B. Since

$$\frac{\arg(AK_S)}{\arg(VK_S)} \simeq \frac{Im(C_3^Z - C_7^Z + C_9^Z + C_5'^Z + C_7'^Z - C_9'^Z)}{Im(C_3^Z + C_7^Z + C_9^Z + C_5'^Z + C_7'^Z + C_9'^Z)} \approx -\frac{Z_A}{Z_V} = +2.6 \quad (15)$$

the NP correction from Z -penguins has the same sign for vector mesons $V = J/\Psi, \Psi'$ as for the axial ones $A = \chi_1, \eta_c$. This correlation holds over the whole (Z_{sb}, Z'_{sb}) parameter space after performing leading log QCD corrections. This is illustrated in Fig. 2, where the NP phases $\arg(AK_S)$ versus $\arg(VK_S)$ are shown for Z -penguins (\times , blue). Also shown is the correlation in another NP scenario (+, green), the MSSM with additional flavor and CP violation in singlet down squark mixing, to be discussed in Section 4.1. We estimate the Z -exchange effect in the difference between decays into axial and vector coupling charmonia as

$$|\sin 2\beta_{AK_S} - \sin 2\beta_{VK_S}| \leq 0.18 \cos 2\beta \quad (16)$$

Available data given in Eq. (4) are not significant yet i.e. the difference of the error weighted average of axial minus vector coupling final states reads as $\sin 2\beta_{AK_S} - \sin 2\beta_{VK_S} = -0.05 \pm 0.26$.

Decays into $\chi_{0,2}$ final states are factorization forbidden modes since by C conjugation and Lorentz invariance

$$\langle \chi_0(0^{++}) | \bar{c} \gamma_\mu c | 0 \rangle = 0, \quad \langle \chi_2(2^{++}) | \bar{c} \gamma_\mu c | 0 \rangle = 0 \quad (17)$$

and their amplitude $\mathcal{A}(\bar{B}^0 \rightarrow \chi_{0,2}\bar{K}^0)$ requires gluon exchange. At order α_s the color suppressed Z -penguins compete with a color enhanced SM contribution from tree level W exchange, thus they are doubly $1/N_C$ suppressed with respect to the factorization

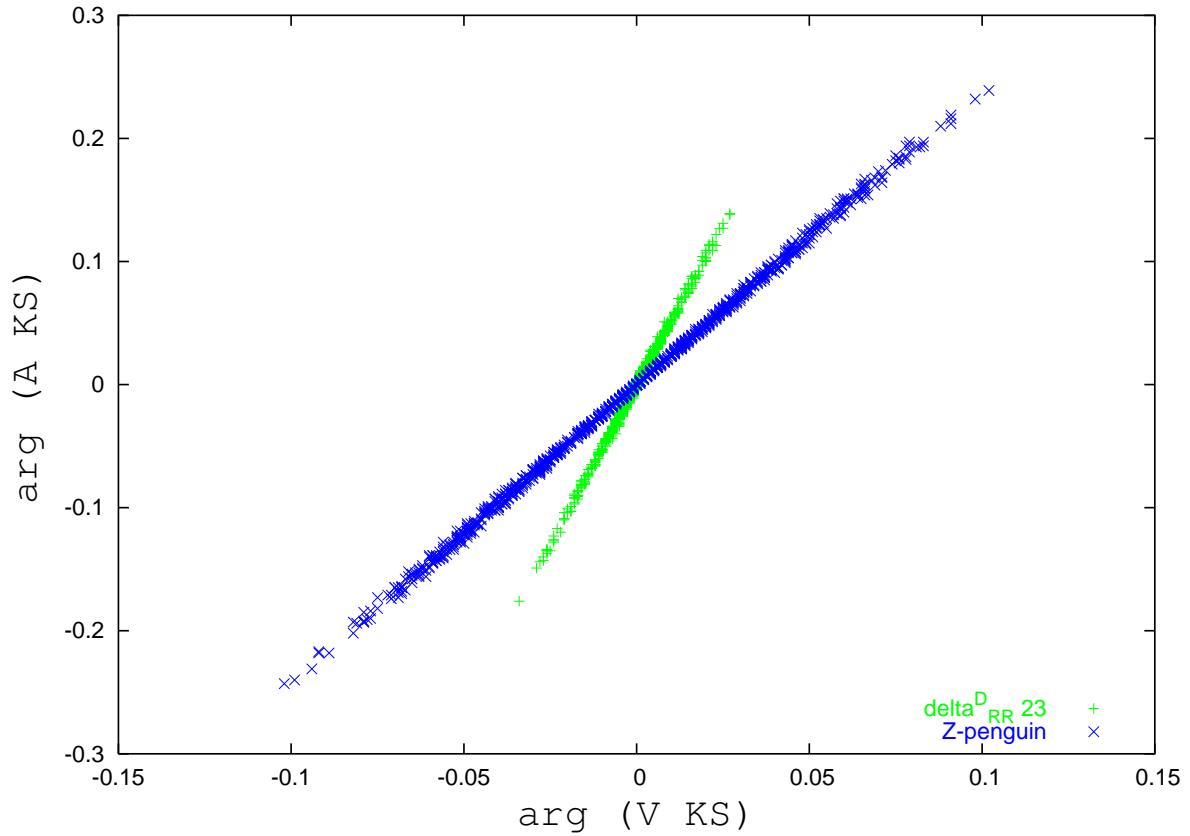


Figure 2: The NP correction for axial coupling mesons $\arg(AK_S)$ as a function of the one for vector coupling mesons $\arg(VK_S)$ induced by non-standard Z -penguins (\times , blue) and in the MSSM with down squark mixing $\delta_{RR\,23}^D$ (+, green) discussed in Section 4.1.

allowed modes. Therefore, the effect of NP from Z -penguins should be least pronounced in $B \rightarrow \chi_{0,2} K_S$ and time dependent CP asymmetries should return in these modes the least polluted value of $\sin 2\beta$ in the $c\bar{c}$ system. However, since naive factorization is badly broken in these modes, it is difficult to be quantitative here. Still, a departure in $\sin 2\beta$ in $\chi_{0,2}$ from the fitted value given in Eq. (2) indicates the presence of NP, as well as any discrepancy in the extracted value of $\sin 2\beta$ among different charmonia.

3.2 Z -penguin effects in the B_s -system

We investigate here implications on 2-body decays in the B_s -system such as $B_s \rightarrow (c\bar{c})\phi$ and $B_s \rightarrow \phi\phi$. The coefficient of the $\sin(\Delta m_{B_s} t)$ term in the time dependent CP asymmetry reads as (see Eqs. (6) and (7) with changes from B_d to B_s -mesons)

$$S_{M\phi} = -\eta(M\phi) \sin(\arg M_{12} - \arg(MK_S)) \quad (18)$$

where we neglected for simplicity the width difference between B_s and \bar{B}_s mesons and as before direct CP violation, i.e. we used $|\bar{\mathcal{A}}/\mathcal{A}| = 1$. In the SM the phase of the mixing amplitude $\arg M_{12}^{SM} = -2\beta_s = -2\lambda^2\eta$ is tiny. Hence, we expect $S_{c\bar{c}\phi}$ and $S_{\phi\phi}$ of $\mathcal{O}(\lambda^2)$ in the SM. The sZb -penguins do have a twofold effect in the B_s -system, on the decay amplitude similarly to the B_d -system and on the $B_s\bar{B}_s$ mixing. Hence, both $\Delta B = 1$ and $\Delta B = 2$ terms in $S_{M\phi}$ receive contributions from the NP. Concerning the latter and employing the notations of [15], we find

$$M_{12}^Z = \frac{\alpha G_F^2 m_W^2}{3\pi^3 \sin^2 \theta_W} B_{B_s} f_{B_s}^2 m_{B_s} \eta_B \left(Z_{sb}^{*2} + Z_{sb}^{\prime*2} + 2Z_{sb}^* Z_{sb}^{\prime*} X \right) \quad (19)$$

Here, $X = 4\bar{P}_1^{LR} = -2.84$ [16] includes differences in the bag factors (taken from lattice [17]) and perturbative QCD corrections of the matrix element between operators with different Dirac structure, $\gamma_\mu L(R) \times \gamma^\mu L(R)$ and $\gamma_\mu L(R) \times \gamma^\mu R(L)$. We find

$$r_Z \equiv \frac{M_{12}^Z}{M_{12}^{SM}} = \frac{4\alpha}{\pi \sin^2 \theta_W S_0(x_t)} \left(\frac{Z_{sb}^{*2} + Z_{sb}^{\prime*2} + 2Z_{sb}^* Z_{sb}^{\prime*} X}{(V_{tb} V_{ts}^*)^2} \right) \quad (20)$$

a correction of up to $|r_Z| \leq 0.5$ w.r.t. the SM.

The analysis of NP on the decay amplitude is analogous to the discussion in Section 3.1. However because the final state in these modes consists of two mesons of spin $\neq 0$, to isolate the CP eigenstate components of the final state one has to perform angular analysis in $B_s \rightarrow M\phi$ decays with $M = J/\Psi, \Psi', \chi_{1,2}, \phi$. Otherwise, there is a dilution in $S_{M\phi}$ from admixture of CP odd and even contributions which diminishes a potential NP effect and introduces an additional uncertainty. None the less, this is an excellent null test of the SM since any large CP asymmetry, even in the data summed over polarization, would indicate the presence of NP. If the particle recoiling against the ϕ is a scalar/pseudoscalar, then of course there is a single amplitude and angular analysis is not required. This would be the case for χ_0 and η_c .

With $\arg M_{12} = \arg(1 + r_Z)$ we find

$$\begin{aligned} 0.42 & \quad \text{for } M = \Psi, \Psi' \dots \\ |S_{M\phi}| \leq 0.47 & \quad \text{for } M = \eta_c, \chi_1 \\ 0.66 & \quad \text{for } M = \phi \end{aligned} \quad (21)$$

The spread in $S_{M\phi}$ between different charmonia is up to 0.15. The corresponding numbers for the case with the flipped helicity Z -coupling Z'_{sb} switched off for all quantities discussed in this section can be seen in Table 2.

3.3 Isospin analysis in $B \rightarrow K\pi$ decays

We start with an analysis in $B \rightarrow K\pi^0$ decays. Isospin analysis relates the decay amplitudes of neutral and charged B mesons as [18]

$$\mathcal{A}(B^0 \rightarrow K^0\pi^0) = B - A, \quad -\mathcal{A}(B^+ \rightarrow K^+\pi^0) = B + A \quad (22)$$

where $B \equiv B_{1/2}$ denotes the $\Delta I = 0$ piece and $A \equiv A_{1/2} - 2A_{3/2}$ is a $\Delta I = 1$ combination of $I_f = 1/2$ and $I_f = 3/2$. Z -penguins do violate isospin and hence will give a significant contribution to A . Is the amount required to explain the anomaly in $B \rightarrow \phi K_S$ i.e. of size comparable to the $\Delta I = 0$ SM QCD penguins allowed by current data? Experimental findings [19] give

$$r \equiv \left(\frac{(\mathcal{B}(B^+ \rightarrow K^+\pi^0) + \mathcal{B}(B^- \rightarrow K^-\pi^0))\tau(B^0)}{(\mathcal{B}(B^0 \rightarrow K^0\pi^0) + \mathcal{B}(\bar{B}^0 \rightarrow \bar{K}^0\pi^0))\tau(B^+)} \right)^{1/2} = 1.03 \pm 0.08 \quad (23)$$

This can be written in terms of a relative strong (weak) phase $\rho(\lambda)$ and ratio $|A/B|$ with relation

$$\cos \lambda \cos \rho = -\frac{1-r^2}{1+r^2} \frac{1+|A/B|^2}{2|A/B|} \quad (24)$$

The 1σ allowed $\cos \lambda, |A/B|$ parameter space for vanishing strong phases is shown in Figure 3. For non-zero ρ the allowed range increases and the constraint disappears for $\cos \rho = 0$. Therefore, large isospin breaking contributions $A/B \sim O(1)$ are currently not constrained by $B \rightarrow K\pi^0$ data if the phase $\lambda \sim O(1)$ is large, if, for example, the NP contribution comes with a non CKM large weak phase.

Another constraint on non-standard Z -penguins can come from $B \rightarrow \pi\pi$, $B \rightarrow K\pi$ data and $SU(3)$ symmetry. These Neubert-Rosner type bounds constrain the ratio

$$R_*^{-1} = \frac{2[\mathcal{B}(B^+ \rightarrow \pi^0 K^+) + \mathcal{B}(B^- \rightarrow \pi^0 K^-)]}{\mathcal{B}(B^+ \rightarrow \pi^+ K^0) + \mathcal{B}(B^- \rightarrow \pi^- \bar{K}^0)} \quad (25)$$

in the presence of isospin and CP breaking NP by

$$R_*^{-1} \geq \left[1 - \bar{\epsilon}_{3/2} \sqrt{(|a| + |\cos \gamma|)^2 + (|b| + |\sin \gamma|)^2} \right]^2 \quad (26)$$

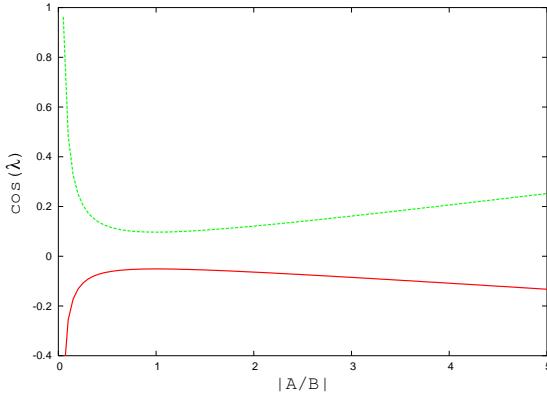


Figure 3: Constraints on isospin violation from $B \rightarrow K\pi^0$ data for vanishing strong phases. The bounds weaken for non-zero strong phases. The range between the curves is allowed at 1σ .

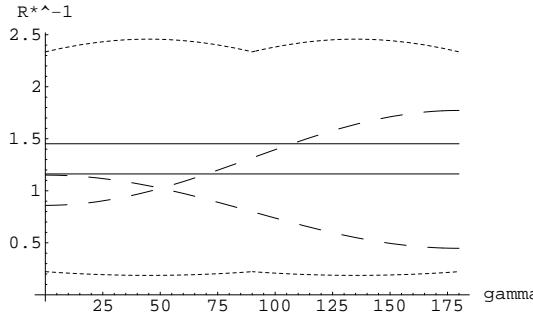


Figure 4: The ratio R_*^{-1} as a function of γ . Shown are the data at 1σ (solid), the bounds in a NP scenario with enhanced and order one CP violating Z -penguins (dotted) and the SM bounds for central values (dashed).

where a, b are CP even (odd) isospin violating contributions, see [20] for details. There is a corresponding upper bound on R_*^{-1} obtained by interchanging the sign in front of the $\bar{\epsilon}_{3/2}$ term. As discussed in Section 3, semileptonic rare $b \rightarrow s\ell^+\ell^-$ decays bound enhanced Z -penguins to be at most 2 to 3 of their value in the SM, i.e. $|a + ib| \lesssim (2 - 3)|a_{SM}|$. Hence, if the SM is allowed, then the upper bound on R_*^{-1} is even less constraining for Z -penguins. However, the lower bound excludes large values of $|a|, |b|$, as can be seen from Eq. (26). For our analysis we find $R_*^{-1} = 1.31 \pm 0.15$, $\bar{\epsilon}_{3/2} = 0.20 \pm 0.02$ using recent data [19] and use $a_{SM} = 0.64$, $b_{SM} = 0$ [20] for the central SM value.

We plot the ratio R_*^{-1} as a function of γ in Fig. 4. Displayed are the 1σ band from data (solid), the NP bounds with $|a| = |b| = 2|a_{SM}|$ (dotted) and for comparison the SM bounds (see [20]) using central values (dashed). We see that for such moderate enhancement of the isospin violating contributions the NP bounds are even weakened compared to the SM, hence irrelevant. Note that in order to accommodate $\sin 2\beta_{\phi K_S} =$

–0.4, one needs order one CP violation, i.e. $|a| \sim |b|$. We checked that our conclusions are stable under variation of the sizes of a, b independently as long as $|a|, |b| \leq \mathcal{O}(10)$.

4 Predictions of Z -penguins vs other NP models

In Sections 3.1 and 3.2 we have discussed the impact of complex, non-standard Z -penguins on time dependent asymmetry measurements $B \rightarrow (c\bar{c})K$ and $B_s \rightarrow (c\bar{c})\phi$ decays. In this Section we discuss further predictions of this NP scenario and compare them with those of other models.

Non-standard Z -penguin effects in $B \rightarrow \phi K_S$ have been first discussed in [8]. Unlike $B \rightarrow (c\bar{c})K$ decays where the chromomagnetic dipole operator is color octet and suppressed, NP in $b \rightarrow s\bar{s}$ decays can enter in both the 4-Fermi and the gluon dipole operators $O_{8g}^{(\prime)}$, see Appendix A and B. We stress that the NP in a scenario with non standard Z -penguins is confined to the 4-Fermi operators, i.e. dominantly in the electroweak penguin O_9 . We checked that the NP effects induced in the dipole operators via leading log RGE mixing are below few percent. This is good since there are substantial theoretical uncertainties related to the matrix element of $O_{8g}^{(\prime)}$. Therefore, if it turns out that there is NP in $B \rightarrow \phi K_S$ decay but not in $b \rightarrow c\bar{c}s$ - something that can be checked by comparing $\sin 2\beta$ from decays into different charmonia - the scenario with non-standard sZb -couplings - and any other who does not have CP violation beyond the SM in the chromomagnetic dipole operator - can be excluded.

The correlation of CP asymmetries in $B \rightarrow \phi K_S$ with decays into charmonium with axial $A = \chi_1, \eta_c$ and and vector coupling $V = J/\Psi, \Psi'$ is shown in Fig. 5. To be specific, we plot $\sin 2\beta_{AK_S} - \sin 2\beta_{VK_S}$ as a function of $\sin 2\beta_{\phi K_S} - \sin 2\beta_{VK_S}$ in the Z -penguins scenario (blue). Also shown is the outcome in the MSSM with down squark mixing $\delta_{RR\,23}^D$ discussed in Section 4.1 for two values of the chromomagnetic α_s matrix element, $\kappa_8 = -0.045$ (red) and $\kappa_8 = -0.030$ (green). Data given in Eqs. (3) and (4) yield

$$\sin 2\beta_{\phi K_S} - \sin 2\beta_{(J/\Psi, \Psi')K_S} = -1.19 \pm 0.42 \quad (\text{Average}) \quad (27)$$

which is also displayed. The correlations shown in Fig. 5 from the two beyond the SM models are very distinct and allow to distinguish between them with improved data.

4.1 Impact of supersymmetric $\tilde{g} - \tilde{d}$ loops on $b \rightarrow c\bar{c}s$ decays

Let us now consider the implications of the MSSM with additional flavor and CP violation beyond the Yukawa couplings on $b \rightarrow c\bar{c}s$ transitions. In particular, let us suppose that there is only mixing between the singlet scalar partners of the down quarks of 2nd and 3rd generation, to be abbreviated here as $\delta_{RR\,23}^D$. This term induces FCNC though gluino-down squark loops. In this scenario, $\delta_{RR\,23}^D$ the only source of beyond the SM CP violation and so this particular framework is rather predictive. For previous studies of gluino mediated effects in $B \rightarrow \phi K_S$ see [21],[22].

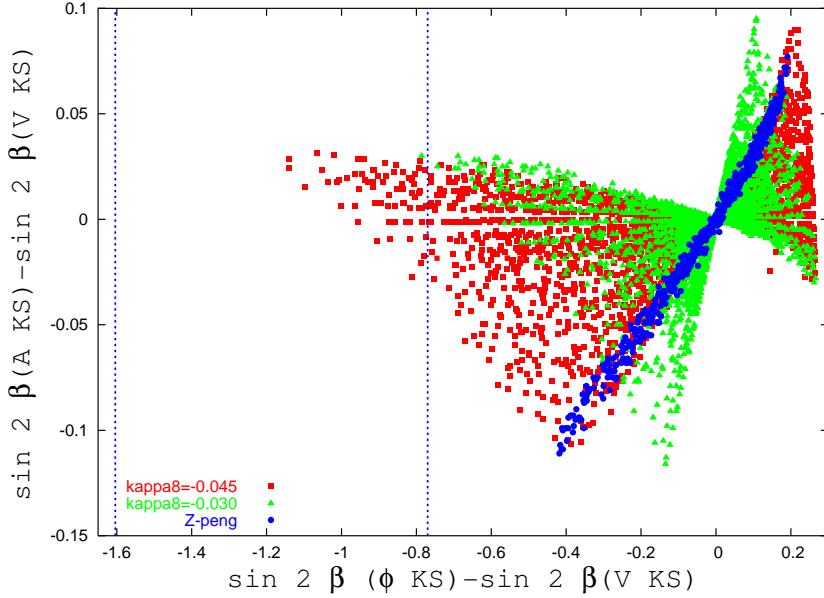


Figure 5: Difference in mixing $[\sin 2\beta_{AK_S} - \sin 2\beta_{VK_S}]$ as a function of $[\sin 2\beta_{\phi KS} - \sin 2\beta_{VK_S}]$ in the non-SM Z -scenario (blue) and in the MSSM with additional flavor violation induced by $\delta_{RR\ 23}^D$. The latter is shown for $\kappa_8 = -0.045$ (red) and $\kappa_8 = -0.030$ (green). Also displayed is the 1σ range from data given in Eq.(27).

The model gives contributions to the flipped 4-Fermi operators $O'_{3\ldots 6}$ and the dipole operators $O'_{7\gamma}$, O'_{8g} . We use the initial conditions at the weak scale given in [23] in the mass insertion approximation. We evolve the coefficients C_i from the SM and C'_i from the NP separately to the m_b scale with the leading log RGE, see e.g [15]. We scan over the squark mass $150\text{GeV} \leq m_{\tilde{q}} < 1\text{TeV}$, the gluino mass $0.2 \leq (m_{\tilde{g}}/m_{\tilde{q}})^2 < 1.3$ and $|\delta_{RR\ 23}^D| \leq 1$ ⁴ with arbitrary phase and include the constraints from data on $\mathcal{B}(b \rightarrow s\gamma)$ following [13], [24]. Numerically, we find

$$|\arg(MK_S)| \leq \begin{cases} 0.04 & \text{for } M = \Psi, \Psi' \cdots \\ 0.20 & \text{for } M = \eta_c, \chi_1 \end{cases} \quad (28)$$

Similar to Z -penguins, the NP effects in decays to axial mesons $A = \chi_1, \eta_c$ are bigger than in the decays to vector mesons $V = J/\Psi, \Psi'$. We find that the relation

$$\arg(AK_S) \simeq +5.2 \arg(VK_S) \quad (29)$$

holds up to a few percent as can be seen in Fig. 2. For the difference in $\sin 2\beta$ we obtain

$$|\sin 2\beta_{AK_S} - \sin 2\beta_{VK_S}| \leq 0.19 \cos 2\beta \quad (30)$$

The correlation with $B \rightarrow \phi KS$ is shown in Fig. 5 for two values of the α_s matrix element of the gluon dipole operator, $\kappa_8 = -0.045$ (red) corresponding to the asymptotic

⁴At large $\tan \beta$ the magnitude of $\delta_{RR\ 23}^D$ is constrained by $B_s \rightarrow \mu^+ \mu^-$ data [25].

ϕ distribution amplitude and $\kappa_8 = -0.030$ (green), the result in a quark model (see Appendix A). This illustrates the sensitivity to hadronic physics in this NP scenario. The difference in $\sin 2\beta$ between axial and vector coupling mesons is limited if the difference between ϕK_S and the vector ones is large and negative. Current data indicate that $\sin 2\beta_{AK_S} - \sin 2\beta_{VK_S} \leq 0.04$. We checked that this upper bound holds up to a value of the gluon matrix element which is 50 percent bigger than our central value $\kappa_8 = -0.045$.

With values possible even greater than 60 ps^{-1} for Δm_s [21], the CP asymmetries in the B_s -system induced by $\delta_{RR\ 23}^D$ can dominate over the SM contribution $15.1 \text{ ps}^{-1} \leq \Delta m_{s\ SM} \leq 21.0 \text{ ps}^{-1}$ @ 95 % C.L. [26]. Therefore, if at all measurable, this framework allows for large non-SM effects in $S_{(c\bar{c})\phi}$ and $S_{\phi\phi}$.

	both	$Z'_{sb} = 0$	both	$Z'_{sb} = 0$
$ \arg(VK_S) $	0.11	0.07	0.05	0.03
$ \arg(AK_S) $	0.25	0.18	0.12	0.08
$ \sin 2\beta_{AK_S} - \sin 2\beta_{VK_S} $	$0.18 \cos 2\beta$	$0.12 \cos 2\beta$	$0.08 \cos 2\beta$	$0.04 \cos 2\beta$
$\sin 2\beta_{\phi K_S} - \sin 2\beta_{VK_S}$	$-0.47 \dots +0.19$	$-0.33 \dots +0.14$	$-0.20 \dots +0.14$	$-0.12 \dots +0.10$
$ r_Z $	0.50	0.16	0.19	0.07
$ S_{V\phi} $	0.42	0.08	0.16	0.02
$ S_{A\phi} $	0.47	0.17	0.21	0.04
$ S_{\phi\phi} $	0.66	0.42	0.36	0.17
$ S_{A\phi} - S_{V\phi} $	0.15	0.10	0.07	0.05

Table 2: Upper bounds on B_d and B_s quantities defined in text in the presence of non-standard Z -penguins. For $\sin 2\beta_{\phi K_S} - \sin 2\beta_{VK_S}$ we show the accessible range. The first two columns are with the current constraints on the sZb couplings given in Eq. (11), whereas in the last two columns we entertain a scenario where $\sqrt{|Z_{sb} + Z_{sb\ SM}|^2 + |Z'_{sb}|^2} \leq |Z_{sb\ SM}|$, i.e., where data on $\mathcal{B}(b \rightarrow s\ell^+\ell^-)$ show no deviation from the SM. In the first and third columns both helicity couplings are present and the second and fourth ones are obtained with $Z'_{sb} = 0$.

5 Conclusions

One of todays most precise information on CP violation in the quark sector i.e. $\sin 2\beta$ given in Eq. (1) is an average over several final states with the same flavor content. While this procedure returns in the SM to very good approximation the same CP- asymmetries, it is wrong in general, for example if NP breaks parity and CP.

We suggest here to study differences in $\sin 2\beta$ among decays $B \rightarrow (c\bar{c})K_S$ into charmonia $\Psi, \Psi', \eta_c, \chi_{0,1,2}$ with branching ratios of order 10^{-3} to search for physics beyond the SM. An order one NP effect in $B \rightarrow \phi K_S$ decay, which is required to explain the

current anomaly Eq. (3) or a similar large departure from the SM, leads to up to $\mathcal{O}(10)\%$ in the $B \rightarrow (c\bar{c})K_S$ amplitude. This is just at the level at which the data agree with the SM, Eqs. (1) and (2). We stress that differences in $\sin 2\beta$ can signal NP independent of improvements in the present error of the CKM fit. One might extend this program and compare CP asymmetries in decays into final states with the same flavor other than $c\bar{c}$.

We have explicitly shown that a NP model with non-standard Z -penguins does indeed split $\sin 2\beta$ among different charmonia, see Eq. (16). We stress that there is a strong correlation in this scenario between non-SM effects in $b \rightarrow c\bar{c}s$ and $b \rightarrow s\bar{s}s$ decays, since both get contributions from the modified 4-Fermi operators. If the ϕK_S anomaly persists, but $\sin 2\beta_{(J/\Psi, \Psi')K_S} - \sin 2\beta_{(\chi_1, \eta_c)K_S}$ vanishes, it model independently indicates the presence of an enhanced chromomagnetic dipole operator [27] which carries a non-CKM CP violating phase. This emphasizes that $b \rightarrow c\bar{c}s$ and $b \rightarrow s\bar{s}s$ decays are complementary when constraining and distinguishing NP. A comparison of $\sin 2\beta$ differences in the non-SM Z -scenario with the ones in the MSSM with gluino mediated FCNCs shows this in Fig. 5. We discussed time dependent studies in the corresponding decays of B_s -mesons, i.e. $B_s \rightarrow \phi\phi$ and $B_s \rightarrow (c\bar{c})\phi$. They show besides a similar effect from a NP weak phase on the decay amplitude one from NP in $B_s\bar{B}_s$ mixing and large effects are possible. The coefficient $S_{c\bar{c}\phi}$ in the CP asymmetry of $B_s \rightarrow (c\bar{c})\phi$ decays can be up to $\mathcal{O}(0.4)$ in the presence of Z -penguins. In $B_s \rightarrow \phi\phi$ decay they induce an asymmetry up to order one, i.e. large as in $B \rightarrow \phi K_S$ decay. Our findings are summarized in Table 2, where we also entertain a scenario where the $b \rightarrow s\ell^+\ell^-$ branching ratio is SM like, hence the bound on the Z -penguins gets tighter $\sqrt{|Z_{sb} + Z_{sb\,SM}|^2 + |Z'_{sb}|^2} \leq |Z_{sb\,SM}|$ (assuming zero errors) than it currently is as given in Eq. (11). There remain sizable effects in the observables discussed in this work, but closer to potential theory SM back grounds. Information on $Z_{sb}^{(\prime)}$ phases also come from the Forward-Backward asymmetry in $B \rightarrow K^*\ell^+\ell^-$ [12] and inclusive $B \rightarrow X_s\ell^+\ell^-$ decays in the long term future.

We studied the effects of non-standard sZb -couplings in an isolated manner. If this generic structure arises from a larger model beyond the SM e.g. the MSSM with additional flavor violation beyond CKM, the signatures can be rather diluted. We recall that order one mixing between the \tilde{c}_L and the \tilde{t}_R squarks can generate via chargino-higgsino loops left handed sZb -couplings near the experimental bound, whereas the right handed couplings are suppressed by the small strange Yukawa [12]. We show for comparison all quantities also with flipped helicity Z'_{sb} switched off in Table 2. The reach of the Z -couplings is sensitive to right-handed currents in particular in the B_s -system, i.e. Δm_s .

In our study of CP violating time dependent asymmetries we neglected NP in transitions between the *first* and third generation down quarks which could affect $B\bar{B}$ mixing. Still, in this case, differences in CP asymmetries among different charmonia manifest the presence of new phases in $b \rightarrow c\bar{c}s$ transitions. Others places where to look for Z -penguins are $\Lambda_b \rightarrow \Lambda\phi$ [28], $\Lambda_b \rightarrow \Lambda(\bar{c}c)$, $B \rightarrow (\bar{c}c)K^*$ and $B \rightarrow \phi K^*$ decays where polarization observables probe the handedness of the NP couplings. There is experimental support for the possibility of large electro weak penguins in $B \rightarrow K\pi$ decays [29], which, for example, could be induced by non-standard Z -penguins.

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A Matrix element of $\bar{B} \rightarrow (c\bar{c})K$ and $\bar{B} \rightarrow \phi K$

The effective Hamiltonian is given as, see e.g. [15]

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1\dots 10, 7\gamma, 8g} (C_i O_i + C'_i O'_i) \quad (\text{A-1})$$

with

$$\begin{aligned} O_1 &= (\bar{c}_{L\alpha} \gamma_\mu b_{L\beta})(\bar{s}_{L\beta} \gamma_\mu c_{L\alpha}) & O_2 &= (\bar{c}_L \gamma_\mu b_L)(\bar{s}_L \gamma_\mu c_L) \\ O_3 &= (\bar{s}_L \gamma_\mu b_L) \sum_q \bar{q}_L \gamma^\mu q_L & O_4 &= (\bar{s}_{L\alpha} \gamma_\mu b_{L\beta}) \sum_q \bar{q}_{L\beta} \gamma^\mu q_{L\alpha} \\ O_5 &= (\bar{s}_L \gamma_\mu b_L) \sum_q \bar{q}_R \gamma^\mu q_R & O_6 &= (\bar{s}_{L\alpha} \gamma_\mu b_{L\beta}) \sum_q \bar{q}_{R\beta} \gamma^\mu q_{R\alpha} \\ O_7 &= \frac{3}{2} (\bar{s}_L \gamma_\mu b_L) \sum_q Q_q \bar{q}_R \gamma^\mu q_R & O_8 &= \frac{3}{2} (\bar{s}_{L\alpha} \gamma_\mu b_{L\beta}) \sum_q Q_q \bar{q}_{R\beta} \gamma^\mu q_{R\alpha} \\ O_9 &= \frac{3}{2} (\bar{s}_L \gamma_\mu b_L) \sum_q Q_q \bar{q}_L \gamma^\mu q_L & O_{10} &= \frac{3}{2} (\bar{s}_{L\alpha} \gamma_\mu b_{L\beta}) \sum_q Q_q \bar{q}_{L\beta} \gamma^\mu q_{L\alpha} \\ O_{7\gamma} &= \frac{e}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu} & O_{8g} &= \frac{g_s}{16\pi^2} m_b \bar{s}_{L\alpha} T_{\alpha\beta}^a \sigma_{\mu\nu} b_{R\beta} G^{a\mu\nu} \end{aligned} \quad (\text{A-2})$$

where the sum is over the active quarks $q = u, d, s, c, b$, and Q_q is their electrical charge in fractions of e and α, β are color indices. The operators O'_i are obtained from flipping $L \leftrightarrow R$ in the O_i .

The matrix element of decays into mesons with vector coupling such as $\bar{B} \rightarrow J/\psi K$ and $\bar{B} \rightarrow \psi' K$ is proportional to (N_C is the number of colors)

$$T = V_{tb} V_{ts}^* \left(C_1 + C_3 + C_5 + \frac{C_2 + C_4 + C_6}{N_C} + C_7 + C_9 + \frac{C_8 + C_{10}}{N_C} \right) + C_i \rightarrow C'_i \quad (\text{A-3})$$

The one describing decays into mesons with axial coupling such as $\bar{B} \rightarrow \chi_1 K$ and $\bar{B} \rightarrow \eta_c K$ can be obtained from Eq. (A-3) by changing the sign of $C_{5,6,7,8}$ and $C'_{1,2,3,4,9,10}$.

The matrix element of $\bar{B} \rightarrow \phi K$ is proportional to

$$\begin{aligned} P &= V_{tb} V_{ts}^* \left(C_3 + C_4 + C_5 + \frac{C_3 + C_4 + C_6}{N_C} - \frac{1}{2} (C_7 + C_9 + C_{10} + \frac{C_8 + C_9 + C_{10}}{N_C}) \right. \\ &\quad \left. + \kappa_2 C_2 + \kappa_8 C_{8g}^{eff} \right) + C_i \rightarrow C'_i \end{aligned} \quad (\text{A-4})$$

where $\kappa_{2,8}$ stem from $\mathcal{O}(\alpha_s)$ corrections to the corresponding matrix element and the effective coefficient of the chromomagnetic operator, C_{8g}^{eff} is defined e.g. in [15]. For NP

scenarios with an enhanced *bsglue*-coupling the matrix element of $O_{8g}^{(t)}$ is particularly important. Keeping only terms leading in the heavy quark limit, we obtain

$$\kappa_8 = -2 \frac{\alpha_s}{4\pi} \frac{N_C^2 - 1}{2N_C^2} \frac{m_b^2}{< q^2 >} = -2 \frac{\alpha_s}{4\pi} \frac{N_C^2 - 1}{2N_C^2} \int_0^1 dx \frac{\Phi_{\parallel}(x)}{1-x} \quad (\text{A-5})$$

in agreement with the QCD factorization [30] calculation by [31]. In the second step we evaluated the averaged momentum square from the gluon propagator $1/< q^2 >$ with $q^2 = m_b^2(1-x)$ and convoluted it with the longitudinal light cone distribution amplitude of the ϕ meson, $\Phi_{\parallel}(x)$, which encodes the momentum distribution of the constituent quarks in the meson, see [32] for details. Here, x denotes the fraction of the ϕ momentum carried by its s -quark. Theoretical uncertainties in κ_8 are from Φ_{\parallel} and more generally, from power corrections to the factorization, which also limit the accuracy of the total amplitude in Eq. (A-4). For asymptotic form $\Phi_{\parallel}(x) = 6(1-x)x$, which is supported by light cone sum rule calculations [32] we obtain $m_b^2/< q^2 > = 3$, bigger than the value from a quark model calculation $m_b^2/< q^2 > \simeq 2$. For our numerical study we use $\kappa_8 = -0.045$ corresponding to the asymptotic distribution amplitude and $\kappa_2 = -0.011 - i0.012$ [33].

B LLog renormalization for Z -penguins

Z -penguins induce the following contributions at the weak scale

$$\begin{aligned} C_3^Z(m_{\text{weak}}) &= \frac{g^2}{4\pi^2} \frac{Z_{sb}^*}{V_{tb}V_{ts}^*} \frac{1}{6} \\ C_7^Z(m_{\text{weak}}) &= \frac{g^2}{4\pi^2} \frac{Z_{sb}^*}{V_{tb}V_{ts}^*} \frac{2}{3} \sin^2 \theta_W \\ C_9^Z(m_{\text{weak}}) &= -\frac{g^2}{4\pi^2} \frac{Z_{sb}^*}{V_{tb}V_{ts}^*} \frac{2}{3} (1 - \sin^2 \theta_W) \\ C_5'^Z(m_{\text{weak}}) &= \frac{g^2}{4\pi^2} \frac{Z_{sb}'^*}{V_{tb}V_{ts}^*} \frac{1}{6} \\ C_7'^Z(m_{\text{weak}}) &= -\frac{g^2}{4\pi^2} \frac{Z_{sb}'^*}{V_{tb}V_{ts}^*} \frac{2}{3} (1 - \sin^2 \theta_W) \\ C_9'^Z(m_{\text{weak}}) &= \frac{g^2}{4\pi^2} \frac{Z_{sb}'^*}{V_{tb}V_{ts}^*} \frac{2}{3} \sin^2 \theta_W \end{aligned} \quad (\text{B-1})$$

Note that non-SM coefficients are treated as lowest order in α_s and α_W coupling constants. RG evolution to the m_b -scale is done with the effective 12 dimensional LLog anomalous dimension matrix, which is given in [15], except for the γ_{ik} , $i = 7, \dots, 10$ and $k = 7\gamma, 8g$ entries. They correspond to the α_s -mixing of electroweak penguins onto

the dipole operators in the basis given in Eq. (A-2) and can be deduced from [34] as ($\gamma = g_s^2/(16\pi^2)\gamma^0$)

$$\begin{aligned}\gamma_{7,7\gamma}^0 &= -\frac{16}{9} & \gamma_{7,8g}^0 &= \frac{5}{6} & \gamma_{8,7\gamma}^0 &= -\frac{1196}{81} & \gamma_{8,8g}^0 &= -\frac{11}{54} \\ \gamma_{9,7\gamma}^0 &= \frac{232}{81} & \gamma_{9,8g}^0 &= -\frac{59}{54} & \gamma_{10,7\gamma}^0 &= \frac{1180}{81} & \gamma_{10,8g}^0 &= -\frac{46}{27}\end{aligned}\quad (\text{B-2})$$

The sectors O_i and O'_i evolve independently with the same anomalous dimension.

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